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Bio-economic evaluation of cropping systems for saline coastal Bangladesh: III Benefits of adaptation in current and future environments

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ABSTRACT

Climate change and salinisation present substantial challenges to the sustainability of cropping systems in south-west coastal Bangladesh. This is the third paper in a series reporting a study to assess the impacts of climate change and salinity on the productivity and economic viability of ten current and potential rice-based cropping systems in two coastal villages in Khulna District. In this paper, possible adaptations are assessed, including novel dry-season crops, changed fertilizer use, and changed sowing dates, across five climate and three salinity scenarios. Farmers' estimated, APSIM-simulated, and extrapolated yield distributions were incorporated in budgets for the ten cropping systems, using current and projected salinity levels. Current and projected future prices and costs were used to estimate different measures of profitability. Estimated variability in yields and prices was used to generate probability distributions for these profitability measures, permitting comparison of cropping systems based on profitability and risk. Adaptation through changed fertilizer use (higher or lower, depending on the crop) was projected to give higher returns for some cropping systems. However, larger improvements were obtainable with changes in sowing dates to avoid the worst stresses imposed by climate change and salinity. The loss of production of all crops except watermelon and pumpkin due to salinity was more than offset with changed sowing dates for 2030 and 2060 conditions, irrespective of season. With such adaptations, and allowing for risk, the rice/shrimp system maintained the top ranking in terms of net income per hectare in 2030 and 2060 and the rice/sunflower system maintained the second ranking. The rice/pumpkin/rice system ranked third for 2030 and fourth in 2060 while the rice/maize system moved up to third in 2060.

1. Introduction

Climate change and salinization present substantial challenges to the sustainability of cropping systems in south-west coastal Bangladesh. This is the third paper in a series reporting a study to assess the impacts of climate change and salinity on the productivity and economic viability of current and potential rice-based cropping systems in two representative coastal villages. The first paper (Kabir et al., 2017a) used biophysical modelling to project crop yields across five climate and three salinity scenarios and the second paper (Kabir et al., 2017b) incorporated these biophysical results into crop budgets to model the economic impacts. In both papers, the modelling assumed a continuation of farmers' current practices (other than the incorporation of new crops). However, there is clear evidence that farmers are already adapting to climate change and salinization, drawing on their own innovations as well as externally-provided technologies (Kabir et al., 2016, 2017c). Hence it is important to incorporate adaptive responses at the farm level in assessing the sustainability of cropping systems. Although, a number of studies have been undertaken on the impacts of climate change on agriculture in Bangladesh (Alam and Ahmed, 2010; Yu et al., 2010; Hussain, 2011; Ruane et al., 2013; Hassan et al., 2014; Lázár et al., 2015), none of these has incorporated possible adaptation options. In this paper, two broad adaptation options are assessed – changes in fertilizer application and changes in sowing dates.

2. Methodology

2.1. Study locations and cropping systems

Two coastal villages with contrasting farming systems in Dacope Sub-district, Khulna District, were selected for the study – Shaheberabad, cultivating rice in the wet season, non-rice crops in the

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Table 1
Cropping systems assessed for Shaheberabad and Uttar Kaminibasia.

Cropping system	Wet season	Dry season	Early wet season	Status
P1	Rice	Watermelon	Fallow	Existing
P2	Rice	Fallow	Fallow	
P3	Rice	Pumpkin	Fallow	
P4	Rice	Watermelon	Rice	
P5	Rice	Pumpkin	Rice	
P6	Rice/fish	Shrimp	Shrimp	
P7	Rice	Rice	Fallow	Former
P8	Rice	Maize	Fallow	Potential
P9	Rice	Sunflower	Fallow	
P10	Rice	Wheat	Fallow	

dry season, and some rice in the early wet season, and Uttar Kaminibasia, cultivating rice in the wet season and brackish-water shrimp in the dry season. Details about the villages and methods of farm-level data collection were presented in Kabir et al., 2017b. Secondary data included historical (1984–2013) climate data (daily mean, maximum, and minimum temperatures, precipitation, and radiation) obtained from the Bangladesh Meteorological Department (BMD). Moreover, historical (2004–2014) soil salinity data were obtained from the Soil Resource Development Institute (SRDI), Bangladesh. Ten cropping systems were examined – six existing, one former, and three potential cropping systems (Table 1). These were described in Kabir et al., 2017a. In this paper, each system is reassessed with some possible adaptation options.

2.2. Adaptations evaluated

As farmers become aware of changes in climate and salinity, they adapt their cropping systems where possible. There are many ways farmers can adapt their cropping systems:

1. Choice of crop varieties and alternative crops
2. Planting time and cropping season duration of rice and dry-season crops
3. Nutrient management (e.g., fertilizer application rates)
4. Timing, amount, and application method of supplementary irrigation
5. Tillage management (e.g., zero till, strip till, reduced till, or raised beds)

Strategy 1 in the list above has already been systematically evaluated insofar as we explored the feasibility of three new crop rotations (P8 to P10 in Table 1) in the preceding papers (Kabir et al., 2017a,b). In this paper, we expand this to include an evaluation of Strategies 2 and 3. Strategy 4 was not explored because widespread access to irrigation for dry-season cropping is constrained in coastal Bangladesh due to saline groundwater, while Strategy 5 requires investment in new machinery that was considered to make this adaptation less attractive than Strategies 1–3.

Key informants interviewed to help select feasible adaptations mentioned that farmers mostly follow their own experience-based fertilizer management for cropping. Scientists often claim that their recommended fertilizer practices will reduce the yield gap. Hence the effects on crop yields of a 10% and 20% increase in nitrogen application over farmers' practice were simulated, along with the doses recommended by researchers from the Bangladesh Rice Research Institute (BRRI) and the Bangladesh Agricultural Research Institute (BARI) for each crop (Table 2).

Changing the sowing date is already a widely-adopted adaptation to climate change in the case-study villages. The key informants noted that farmers regulate the sowing date of crops in order to fit the cropping system with the shift in wet season based on their own experience. Coastal farmers now usually plant their WS rice crop around 2–3 weeks beyond the sowing date recommended by the BRRI due to their experience of a delay in the WS (Kabir, 2016; Kabir et al., 2017c). However, farmers' reported crop yields were mostly lower than potential yields (Kabir, 2016). Hence yields were simulated for early (15 July), recommended (1–15 August), farmers' practice (1–10 September), and very late (15 September) sowing options. Various sowing options were modelled for EWS rice, DS rice, sunflower, maize, and wheat as shown in Table 2.

The above adaptations were subjected to an analysis across five climate scenarios to assess their current and future technical feasibility, together with an assessment of their current and future economic viability, assuming on-going salinization of the environment as estimated in Kabir et al. (2017a).

2.3. Modelling

As described in Kabir et al. (2017a), the Agricultural Production Systems Simulator (APSIM) crop simulation model was used to simulate biomass and grain yields over a 30-year period for both historical and projected future climate and salinity scenarios. Scenarios were developed for 2030 and 2060 based on the IPCC's A1 (pessimistic) and B2 (optimistic) emissions scenarios. The historical simulation outcomes were validated using the farm-level data collected during the case studies. For calibration of crop varieties in this study, the calibrations already used in the Adaptation to Climate Change in Asia (ACCA) project were applied. This process is described in detail in the ACCA Final Report (Van Wensveen et al., 2015) and in Gaydon et al. (2013, 2017). The impact of salinity, in particular on dry season (DS) and early wet season (EWS) crops, was assessed across historical (2004–2014) and two future (2030 and 2060) salinity scenarios as soil and water salinity substantially affect the crops grown in those seasons. However, only the “without-salinity” scenario was developed for wet season (WS) rice as soil and water salinity fall to very low levels in the WS after the

Table 2
Adaptation options evaluated through possible planting time and nutrient management of rice and dry season crops.

Adaptation options		Crops					
		WS rice	EWS rice	DS rice	Sunflower	Maize	Wheat
Sowing/planting date[a]	Early	15 Jul		15 Nov–25 Dec			
	Recommended	1–15 Aug	Mar 15–April	1–15 Jan	15 Nov–15 Dec	15–30 Nov	15–30 Nov
	Late				15 Dec–15 Jan	7–21 Dec	7–15 Dec
	Farmers' practice	1–7 Sep	1–15 May	1–15 Feb	21–30 Jan	21 Dec–5 Jan	21 Dec–5 Jan
	Very late	15 Sep	Jun 1	28 Feb	28 Feb-31 Mar	30 Jan – 28 Feb	
	Extreme late			Mar–Apr		30 Mar–April	21–30 Jan
Nitrogen dose	Recommended dose compared to farmers' practice	133% increase for P3, P4, and 6% increase for others	30% increase	7% increase	16% decrease	33% decrease	8% decrease

[a] Transplanting date for WS and DS rice,

commencement of monsoon precipitation.

APSIM was used to simulate the impacts of salinity on DS rice and EWS rice as APSIM has recently been enhanced to model the rice salinity response (Radanielson et al., 2016). The impact of salinity on other DS crops such as maize, sunflower, and wheat was assessed through a custom-developed salinity response function applied to APSIM outputs (as discussed in Kabir et al., 2017a), as the model does not currently attempt to simulate salinity impacts on those crops. APSIM does not currently have the capacity to simulate performance for some of the existing DS crops such as watermelon, pumpkin and aquaculture (shrimp and fish). Hence yields of watermelon, pumpkin, shrimp and fish under changed future conditions have been based on previous published and unpublished research as well as the perceptions of key informants and expert personnel experienced in coastal farming systems. The basis for these estimates is discussed together with the presentation of results below.

2.4. Marginal analysis

Marginal analysis was conducted to see if the yield responses obtained through the postulated adaptive fertilizer responses were economic (CIMMYT, 1988). The costs of nitrogen fertilizer and labour were counted as paid-out costs and the value of grain was counted as the price of grain in the relevant scenario multiplied by the simulated yield to give the gross benefit for each treatment. The marginal rate of return (MRR) of the undominated treatments was estimated for each of the crops. That is, where a treatment gave a negative marginal rate of return it was deemed to be dominated and subsequent marginal calculations were made relative to the immediately previous undominated treatment. A conservative benchmark MRR of 100% or above was considered an acceptable return to farmers for the additional investment and risk (CIMMYT, 1988). In some cases, the MRR is still above 100% at the highest rate of nitrogen application considered, meaning it may be beneficial for growers to apply even higher rates than the highest currently evaluated.

2.5. Enterprise and stochastic budgeting

Farmers' estimated, APSIM-simulated, and extrapolated yield distributions were incorporated in the budgets for the ten cropping systems, using current and projected salinity levels. The APSIM-simulated typical seasonal yields of WS rice, DS rice, EWS rice, maize, sunflower and wheat were used across the five climate/salinity scenarios. Farmers' estimated and extrapolated typical seasonal yields of watermelon, pumpkin, shrimp, and fish were used as APSIM is incapable of modelling these crops. For purposes of this analysis, the two case-study villages were treated as one combined setting, with suitable environments for either shrimp farming or irrigated cropping in the dry season. Similarly, only one intermediate farm size was considered (1 ha) which was close to the mean farm size in the two villages and broadly representative of farmers' circumstances in the region.

The projection of future prices and costs was not straightforward, given highly complex interactions involving many variables apart from climate change and salinity. Hence future prices of the modelled crops and costs of the major farm inputs (labour, fuel, and fertilizer) were estimated as well as possible through an examination of secondary sources. Farmers' estimated average input costs and output prices were used for the historical scenario. The estimation of future prices and costs is described in Kabir et al., 2017b.

To estimate the riskiness of returns to each cropping system, triangular probability distributions of yield and price were estimated, with the lower limit as the estimated worst case, the mode as the perceived most likely outcome, and the upper limit as the best case, and Monte Carlo simulation was applied using the software package @RISK. Stochastic efficiency analysis was carried out to evaluate the risk-return trade-offs by comparing the cumulative probability distributions of the alternative enterprise choices (Anderson et al., 1988; Hardaker et al., 2004). The details about yields and prices for stochastic budgeting and the rules for determining first-degree stochastic dominance (FSD) and second-degree stochastic dominance (SSD) were discussed in Kabir et al. (2017b). Given the global nature of the markets for the major crops produced, and the complex array of factors affecting future demand and supply, there was no reason to expect correlation between quantity and price variables within any one scenario.

3. Results and discussion

3.1. Adaptation to climate change and salinization

3.1.1. Adaptation through N fertilizer management

The modelling results showed no response of maize yield to increased nitrogen, indicating that farmer application rates were probably already non-limiting; hence maize is not discussed further in this section. Rice and other crops showed apparent and plausible (if not always statistically significant) responses to changes in nitrogen application, sufficient to warrant some discussion and to be subjected to economic analysis in Section 3.2.1.

The yield of WS rice under different cropping systems increased 1–7% with a 10% nitrogen increase and 2–13% with a 20% nitrogen increase across the five climate scenarios (Fig. 1a, b, and c). Overall yield response was most positive in P1, P2, and P3 using the BRRI recommendations but in P4, P5, P7 and P8 the response was apparently negative, perhaps reflecting that there is enough nitrogen available in the fields for these cropping systems. There were no significant differences between climate scenarios. The results indicate that alternative rotations had a much bigger effect on WS rice yields than fertilisation rates.

The yield of EWS rice responded little to a 10% nitrogen increase but not to a further 10% and not at all or even negatively to the BRRI recommended nitrogen rate (in this case, a 30% increase) (Fig. 2). A 10% nitrogen increase gave 3–5% higher yield across all the climate scenarios but 5–7% lower yield with the recommended nitrogen. This may be because there was enough nitrogen in the field already, hence the additional nitrogen increased vegetative growth but produced lower grain yield than with the farmers' practice. The agricultural officer of Dacope Upazila explained that there is plenty of residual fertilizer in the soil after harvesting the fertilizer-intensive DS crops such as watermelon and pumpkin. In addition, the biomass of these crops adds nitrogen to the soil. The soil analysis gave results consistent with this perception; these data were used in the modelling.

In contrast, DS rice yield responded positively to increased nitrogen under all future climate scenarios, though not under historical climate conditions (Fig. 3). The yield responses were very similar for all three nitrogen doses (7%, 10% and 20% increase over farmers' practice) under each climate scenario. This may be because the nitrogen absorption process of the DS rice crop is affected by salinity under farmers' current management, hence there is no further response beyond the recommended 7% increase in nitrogen but nor is there a negative biophysical impact of higher doses. The yields were 11–13% higher in 2030 and 24–26% higher in 2060, implying an interaction between climate change and nitrogen response, presumably due to the CO_2 fertilisation effect.

In the case of sunflower, yields responded to both a 10% and a 20% increase in nitrogen (Fig. 4). The yields were 3–10% higher across the five climate scenarios for a 20% increase in nitrogen over farmers' practice. It was noteworthy that the yield response was somewhat reduced in the optimistic (B1) scenario, especially in 2060, due to less atmospheric CO_2 than under A2. The BARI recommended dose, despite being 16% lower in total, gave 2–7% higher yields across the five climate scenarios. This was because researchers recommended applying half the nitrogen as a basal dressing and the remainder split into two equal top dressings, while the farmers applied less than one third as a

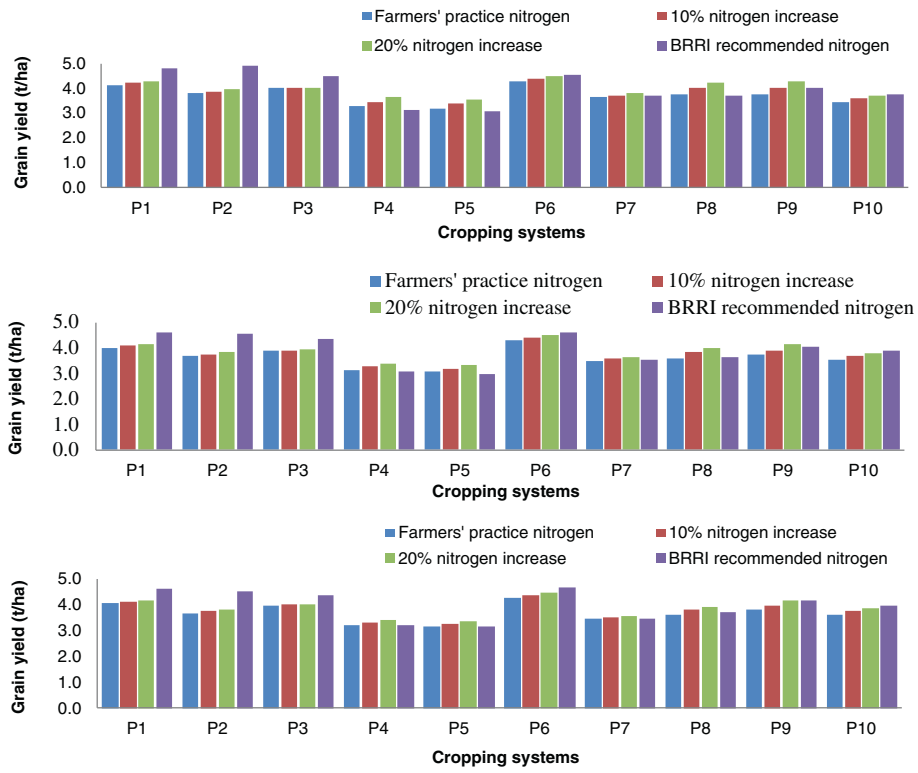

Fig. 1. Grain yield of wet-season rice under farmers' practice and increased nitrogen doses across climate scenarios – (a) historical (1984–2013); (b) 2030 (mean of A2 and B1); and (c) 2060 (mean of A2 and B1). Note: Error bars show one standard deviation from the mean (30 years). Bangladesh Rice Research Institute (BRRI) recommended nitrogen was 133% higher than farmers' practice for P3 and P4 and 6% for other cropping systems.

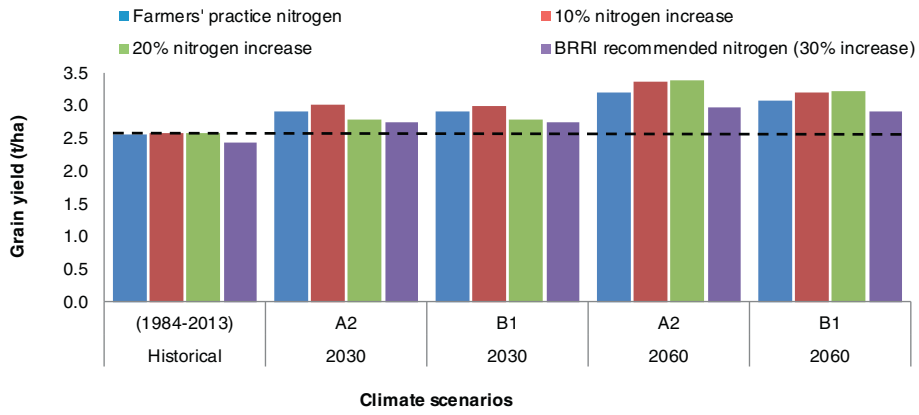

Fig. 2. Grain yield of early wet-season rice under farmers' practice and increased nitrogen doses across five climate scenarios. Note: Error bars show one standard deviation from the mean (30 years). Dotted line shows historical yield with farmers' practice for comparison with other doses and climate scenarios. BRRI = Bangladesh Rice Research Institute.

basal dressing and the timing of their topdressings differed from the recommended timing. Thus the time of application was as important as the dose. However, most farmers were unaware of the BARI recommendations.

The yield of salt-tolerant wheat responded positively to a 20% increase in nitrogen over farmers' current practice (Fig. 5). The yields were 4–5% higher with a 10% nitrogen increase and 8–9% higher with a 20% increase across the five climate scenarios. On the other hand, the BARI recommended nitrogen dose for wheat was 8% lower than farmers' current practice but the yields were 5–6% higher. Again, this was because the researchers' recommendation was to apply two thirds of the nitrogen as a basal dressing and one third as a top dressing while the farmers split the nitrogen into three doses with application times that differed from the recommended times.

3.1.2. Adaptation through changing sowing date

3.1.2.1. Wet season rice. Following the BRRI recommended date, WS rice yield was 0.8 t/ha higher than with the farmers' date under historical conditions, a penalty of 23% (Fig. 6). However, the benefit of the recommended date decreased to 0.3–0.4 t/ha across the 2030 climate scenarios and there was little or no yield difference for the 2060 climate scenarios. Moreover, the variability of yield was greater at the recommended date, particularly in the 2030 and 2060 scenarios, reflecting the increased erraticism of the rainfall pattern during WS rice cropping. The early transplanting option gave consistent yield and less seasonal variability, hence may be a feasible way to enable earlier establishment of the following DS crop. In the simulations, however, there was an implicit assumption that water was available for nursery establishment on 15 June. In reality this may not always be the case. Conversely, even the very late transplanting option could be productive for three-crop systems but with the incorporation of delayed sowing for suitable DS crops like pumpkin.

3.1.2.2. Dry season rice. Both early and late transplanting gave greater yield of DS rice in all climate scenarios (including historical) (Fig. 7). The average yield benefit of the early transplanting (15 November-25 December) was 1.5–2.1 t/ha (45–65%), of very late transplanting (28 February) was 1–1.7 t/ha (31–52%), and of extreme late transplanting

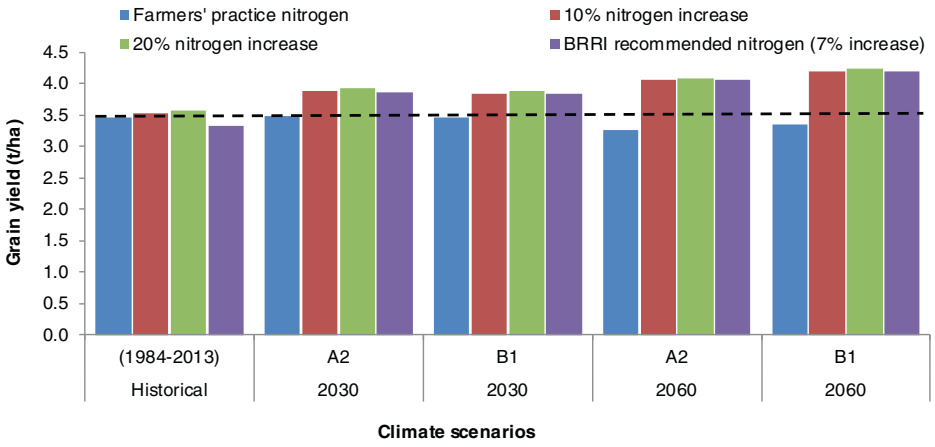

Fig. 3. Dry-season rice under farmers' practice and increased nitrogen doses across five climate scenarios. **Note:** Error bars show one standard deviation from the mean (30 years). Dotted line shows historical yield with farmers' practice for comparison with other doses and climate scenarios. BRRI = Bangladesh Rice Research Institute.

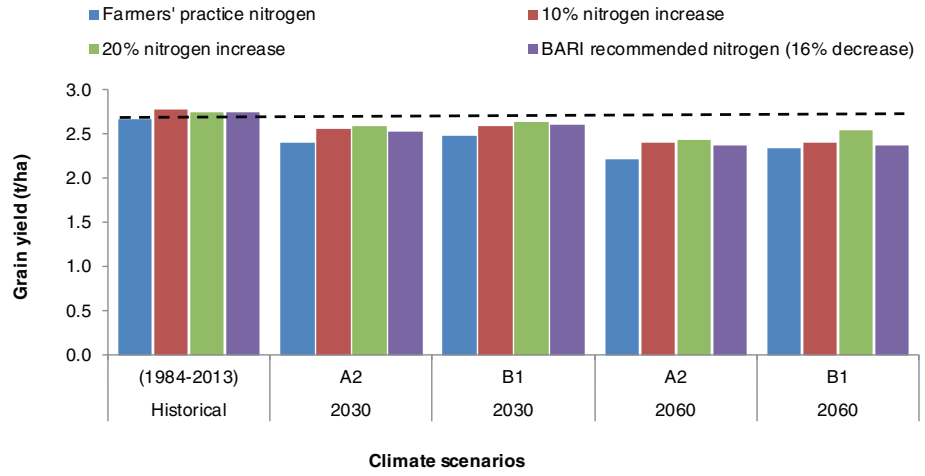

Fig. 4. Sunflower grain yields under farmers' practice and other nitrogen doses across five climate scenarios. **Note:** Error bars show one standard deviation from the mean (30 years). Dotted line shows historical yields with farmers' practice for comparison with other doses and climate scenarios. BARI = Bangladesh Agriculture Research Institute.

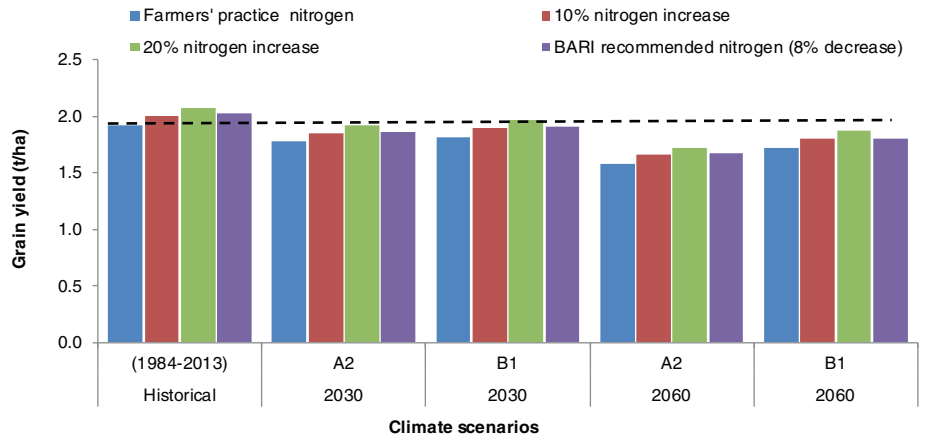

Fig. 5. Wheat grain yields under farmers' practice and other nitrogen doses across five climate scenarios. **Note:** Error bars show one standard deviation from the mean (30 years). Dotted line shows historical yields with farmers' practice for comparison with other doses and climate scenarios. BARI = Bangladesh Agriculture Research Institute.

(31 March-30 April) was 2.6–3.3 t/ha (58–101%) compared with the farmers' sowing date. It was also the case that both the early and extreme late transplanting options gave both higher yield and lower seasonal variability.

This result indicates that the salinity-induced yield loss discussed in Kabir et al. (2017a) could be more than offset through changes in sowing date. This can be explained by the favourable conditions at early transplanting, in particular low soil and water salinity, adequate soil moisture, and lower temperature, resulting in better yield. Conversely, with extreme late transplanting, the projected increase in precipitation not only reduces salinity and soil moisture stress but also creates a more favourable environment for increased nitrogen and water-use efficiency by flushing out salinity from the topsoil and/or diluting the salinity of irrigation water. Hence, the extreme late transplanting option would be more efficacious where the cropping system includes only two crops (rice/rice). This is because DS rice gives higher yield and less seasonal variability under the extreme late transplanting option while the timing of the following crop (WS rice) would not be affected. The fallow period after harvesting WS rice could be used for grazing cattle or short-duration leafy vegetable crops like stem amaranth and Indian spinach.

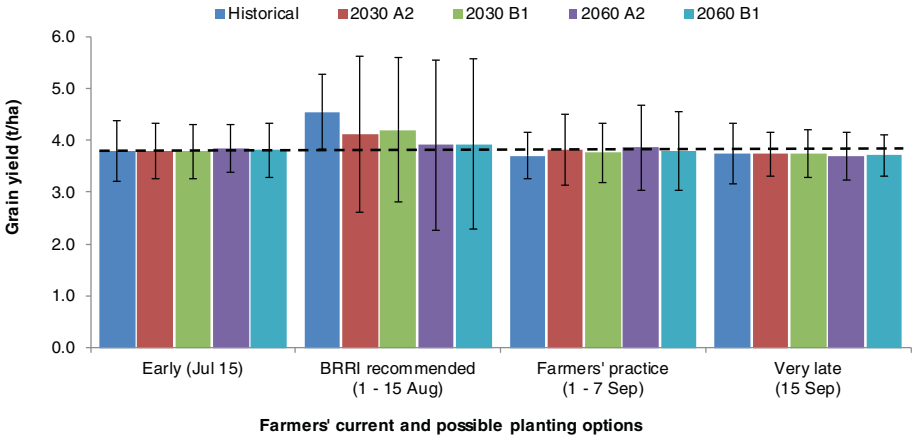

Fig. 6. APSIM simulated yields of wet season rice under farmers' current and possible sowing options across the five climate scenarios. **Note:** Error bars show one standard deviation from the mean (30 years). Dotted line shows historical yield with farmers' practice. BRRI = Bangladesh Rice Research Institute.

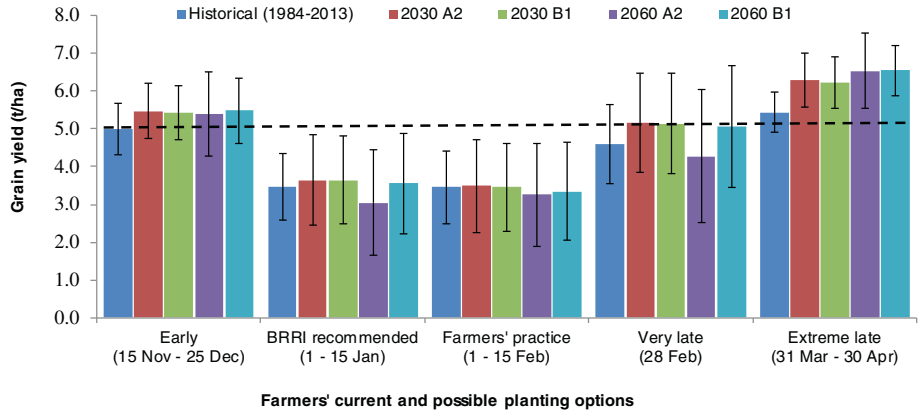

Fig. 7. APSIM simulated yields of dry season rice with salinity under farmers' current and possible sowing options across the five climate scenarios. **Note:** Error bars show one standard deviation from the mean (30 years). Dotted line shows historical yield with farmers' practice. BRRI = Bangladesh Rice Research Institute.

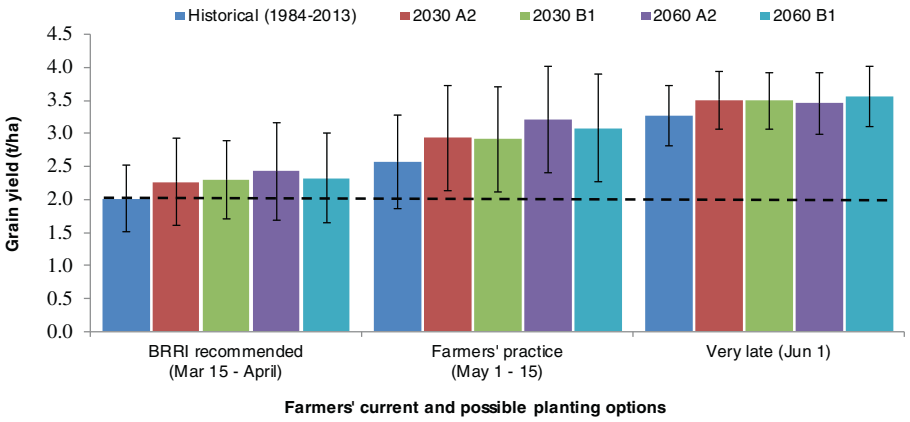

Fig. 8. APSIM simulated yields of early wet season rice with salinity under farmers' current and possible sowing options across the five climate scenarios. Note: Error bars show one standard deviation from the mean (30 years). Dotted line shows historical yield with farmers' practice. BRRI = Bangladesh Rice Research Institute.

3.1.2.3. Early wet season rice. Successively later sowing of EWS rice gives increasingly higher yield across all climate scenarios (Fig. 8). The very late sowing (1 June) gives 20% higher (0.6 t/ha) yield in 2030 and 8–16% higher (0.3–0.5 t/ha) yield in 2060 compared with farmers' sowing date, while the BRRI recommended sowing date resulted in lower yield in all five scenarios. The very late sowing option not only produced higher yield but also showed less seasonal variability. This could be because moisture stress and salinity inhibit the performance of EWS rice when planted on the recommended date, whereas very late sowing enables the crop to escape such stresses due to higher precipitation. The higher precipitation with very late sowing may offset the indirect effect of rising temperature on moisture stress as well as reducing salinity. Decreased rainfall and increased erraticism of the rainfall pattern at the recommended date may be the cause of the poor performance (lower yield and higher seasonal variability) with that sowing date.

The very late sowing option could be effective for three-crop systems as very late sowing gave higher yield with less seasonal variability but would not affect the yield of WS rice as the very late sowing option for WS rice (15 September) also gave consistent performance across all future scenarios. Delayed sowing of WS rice might affect the succeeding DS crops, but late sowing of suitable DS crops like pumpkin might be effective in a three-crop system. Despite some yield loss, the farmers' sowing date might be a better option when two rice crops are combined with early sowing of DS crops like watermelon, as most DS crops showed much better performance under early sowing (see below).

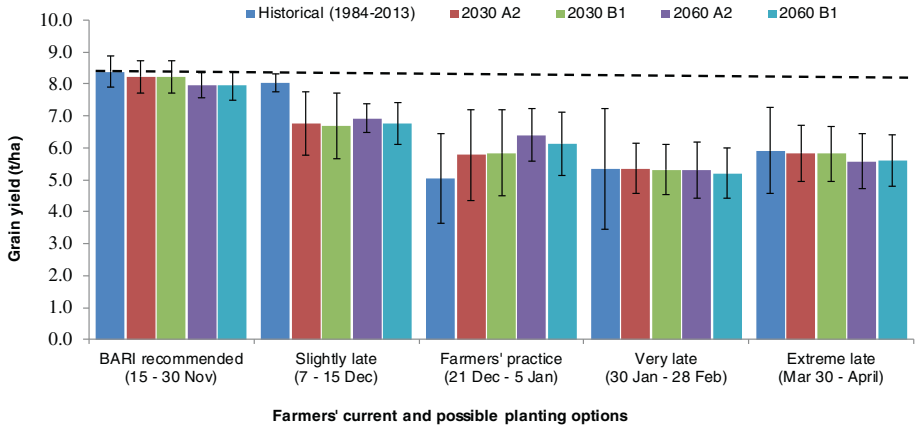

Fig. 9. APSIM simulated yields of maize with salinity under farmers' current and possible sowing options across the five climate scenarios. Note: Error bars show one standard deviation from the mean (30 years). Dotted line shows historical yield with farmers' practice. BARI = Bangladesh Agriculture Research Institute.

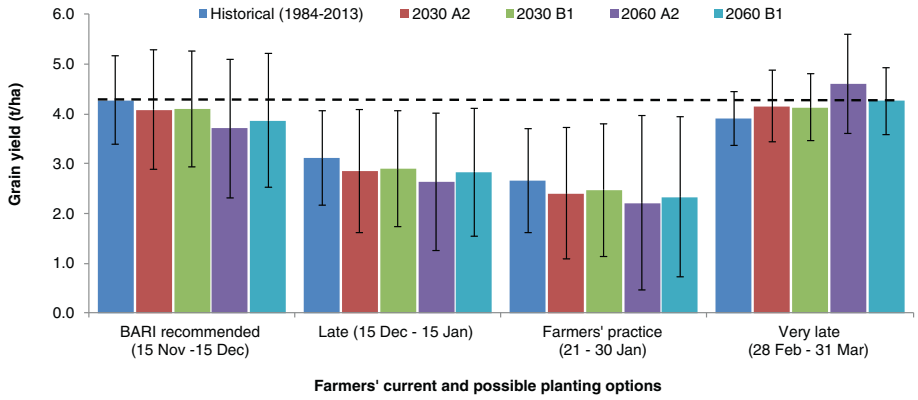

Fig. 10. APSIM simulated yields of sunflower with salinity under farmers' current and possible sowing options across the five climate scenarios. **Note:** Error bars show one standard deviation from the mean (30 years). Dotted line shows historical yield with farmers' practice. BARI = Bangladesh Agriculture Research Institute.

3.1.2.4. Maize. For maize, BARI recommended sowing (15–30 November) gave a yield benefit of 3.4 t/ha (66%) compared with the farmers' sowing date (21 December–5 January) under historical conditions (Fig. 9). The yield advantage of following the BARI recommended sowing date was 2.4–2.5 t/ha (41–43%) in 2030 and 1.6–1.8 t/ha (24–30%) in 2060. It was also the case that "slightly late" sowing (7–15 December) gave yields 0.8–1 t/ha higher across 2030 conditions and 0.5–0.6 t/ha higher across 2060 conditions than with the farmers' (later) sowing date across the same climate scenarios. Seasonal yield variability for the recommended and slightly late crops was also lower than for the other sowing options across all climate scenarios.

This indicates that the yield loss due to salinity under farmers' practice (Kabir et al., 2017a) could be offset by shifting the sowing date earlier as recommended by BARI. The yield loss due to salinity decreased to 1.0–1.3 t/ha (16–21%) instead of 2.9–2.9 t/ha (45%) across the 2060 climate scenarios only by changing the sowing date to 15–30 November, as recommended by BARI. The possible causes of better projected performance of maize with the recommended sowing date are that the levels of soil and water salinity and temperature remain lower than the threshold levels for the crop, while the soil contains adequate moisture at that time. Thus, the crop not only escapes stress (moisture, salinity, and temperature) but also increases the nitrogen- and water-use efficiency because of lower levels of salinity.

These results indicate that following the BARI recommended sowing date could be highly productive for the two-crop systems (WS rice/maize/fallow). However, the wet coastal soils and the delay in harvesting WS rice could be potential constraints to adopting this sowing option. Nevertheless, early drainage of the WS rice fields through constructing drains or sowing short-duration WS rice could facilitate preparing the land for sowing DS crops early. Conversely, the slightly late (7–15 December) sowing option could be more effective where the cropping systems include only two crops. This is because maize gives higher yield with less seasonal variability than with farmers' sowing date and farmers can manage sowing maize at this time without any investment for drainage infrastructure and/or changing the variety of WS rice.

3.1.2.5. Sunflower. The early sowing (15 November-7 December) of sunflower as recommended by BARI gave a projected yield benefit of 1.6 t/ha under historical climate, 1.6–1.7 t/ha (66–70%) in 2030, and 1.5 t/ha (66–68%) in 2060 compared with farmers' later sowing (21–30 January) (Fig. 10). The yield advantage of very late sowing (28 February–30 March) was very similar, again across all climate scenarios. This result indicates that shifting the sowing date forward as recommended by BARI or even later than practised by farmers could give higher yields currently, independently of climate change. The seasonal yield variability of the late-planted crop was also projected to be lower than that of the other sowing options across all climate scenarios.

The favourable conditions (lower levels of salinity, adequate soil moisture, and lower temperature) with the recommended sowing date would explain the better performance. Similarly, adequate rainfall during the very late sowing of sunflower enables the crop to escape the adverse impacts of soil moisture stress and salinity. Despite greater yield benefit, coastal farmers may not be able adopt the recommended sowing option due to the same constraints as for maize. Hence the very late sowing option (28 February–30 March) could be a more efficacious adaptation option for the two-crop system (WS rice/sunflower). The very late sowing gives higher yield with less seasonal variability, while the timing of the following crop (WS rice) would not be affected. In addition, farmers could implement this option very easily and, again, the fallow period after harvesting WS rice could be used for grazing cattle or short duration leafy vegetable crops like stem amaranth and Indian spinach.

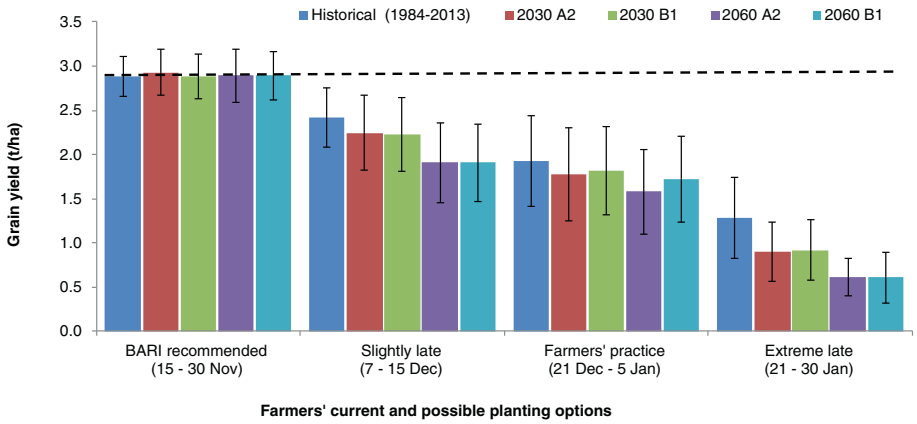

Fig. 11. APSIM simulated yields of wheat with salinity under farmers' current and possible sowing options across the five climate scenarios. Note: Error bars show one standard deviation from the mean (30 years). Dotted line shows historical yield with farmers' practice. BARI = Bangladesh Agriculture Research Institute.

Table 3
Marginal return to fertilizer treatments for WS rice in five climate/salinity scenarios.

Scenario	Treatment	Nitrogen (kg/ha)	Yield (kg/ha)	Paid-out cost	Marginal cost	Net benefit	Marginal net benefit	Marginal rate of return
				BDT/ha				%
Historical (1984–2013)	T2	165	3.78	3800		62,700		
	T1	176.5	3.88	4030	230	64,220	1520	661
	T3	181.5	3.67	4180	150	64,070	(150)	Dominated
	T4	198	3.67	4560	530	65,440	1220	230
2030	T2	165	3.75	5275		72,826		
	T1	176.5	3.83	5594	319	70,396	(2430)	Dominated
	T3	181.5	3.75	5803	528	74,410	1584	300
	T4	198	3.99	6330	527	73,882	(528)	Dominated
2060	T2	165	3.83	6210		105,994		
	T1	176.5	4.49	6586	376	102,585	(3409)	Dominated
	T3	181.5	4.89	6831	621	106,971	977	157
	T4	198	4.55	7452	621	107,784	813	131

T1: researcher-recommended, T2: farmers' practice, T3: 10% over T2; T4: 20% over T2.
1 USD = BDT 78.2 in June 2013. Note: Paid-out costs are the expenses on nitrogen fertilizer and hired labour. Net benefit is the gross benefit minus paid-out costs. Marginal net benefit is the additional net benefit from an addition to paid-out cost.

3.1.2.6. Wheat. Yields were modelled for recommended (15–30 November), late (7–15 December), farmers' practice (21 December–5 January) and very late (21–30 January) sowing options. Bringing the sowing date forward could substantially reduce yield loss due to climate change and salinity (Fig. 11). The early sowing option as recommended by BARI gave a yield benefit of 1 t/ha (20%) under historical climate and 1.1–1.3 t/ha (59–83%) across the future conditions. The relative yield advantage of slightly late sowing over farmers' sowing was 0.2–0.5 t/ha (11–26%) across all climate scenarios. Moreover, seasonal yield variability was lower with the BARI recommended sowing.

This result indicates that shifting the sowing date forward not only offsets adverse climatic and salinity impacts but also gives higher yield compared with farmers' practice, even in the (hypothetical) absence of salinity. The BARI recommended option (15–30 November) could be beneficial (higher yield with less seasonal variability) for the two-crop system (WS rice/wheat/fallow) but the same constraints (e.g., wet soil) as for maize and sunflower would be practical barriers to adopting this sowing date. Thus, slightly late sowing (7–15 December) could be a plausible and productive option for the two-crop system, with due consideration given to the issue of wet soil due to excess rain in the late wet season and poor drainage facilities, and the option of late sowing of WS rice.

3.2. Economic viability of cropping systems with adaptation and mitigation

The net impacts of climate change and salinization on the profitability of cropping systems under farmers' current practice was analysed in Kabir et al. (2017b). In this section, the relative profitability of cropping systems is analysed assuming the two types of adaptation modelled in Section 3.1 – modifying nitrogen application rates and changing sowing dates. In addition, the results of modelling crop performance in the absence of salinity, that is, assuming that salinity could be mitigated, were also subjected to economic analysis. This mitigation scenario may seem highly unrealistic, but it is an exploratory analysis of the maximum potential impacts of salinity mitigation at the regional level, assuming this could be achieved through major investments in river-basin and coastal infrastructure and improved cross-border arrangements affecting freshwater flows from upriver.

3.2.1. Marginal returns of fertilizer options

As described above, APSIM was used to simulate yield responses of WS rice, DS rice, EWS rice, maize, sunflower, and wheat to four nitrogen options or "treatments": T1 – researcher recommended; T2 – farmers' practice; T3 – a 10% increase over farmers' practice; and T4 – a 20% increase over farmers' practice across the five climate scenarios. Note that the researcher-recommended rates were not necessarily the highest rates, depending on the crop considered. APSIM was not capable of simulating yield responses of other DS crops such as watermelon and pumpkin, nor was there any attempt to model the response of shrimp to increased fertilizer use. The APSIM-simulated yields for 2030 and 2060 were averaged across the pessimistic and optimistic scenarios.

Marginal analyses for the three possible rice crops are presented in Tables 3, 4 and 5. A 100% MRR was taken to be the minimum acceptable return. Thus, for WS rice, T4 was the optimal treatment under historical conditions, T3 in 2030, and T4 in 2060 (Table 3). This indicates that a 10–20% increase in N application over farmers' practice

Table 4
Marginal return to fertilizer treatments for EWS rice in five climate/salinity scenarios.

Scenario	Treatment	Nitrogen (kg/ha)	Yield (ton/ha)	Paid-out cost	Marginal cost	Net benefit	Marginal net benefit	Marginal rate of return
				BDT/ha				%
Historical (1984–2013)	T2	131	2.57	3120		39,780		
	T3	144	2.57	3432	312	39,468	(312)	Dominated
	T4	157	2.58	3744	624	39,156	(624)	Dominated
	T1	175	2.43	4170	1050	35,430	(4350)	Dominated
2030	T2	131	2.91	4323		56,892		
	T3	144	3.00	4755	432	58,570	1678	388
	T4	157	2.79	5188	433	58,138	(432)	Dominated
	T1	175	2.75	5778	1023	53,326	(5244)	Dominated
2060	T2	131	3.13	5122		92,084		
	T3	144	3.29	5634	512	94,604	2520	292
	T4	157	3.31	6146	512	94,092	(512)	Dominated
	T1	175	2.95	6846	1212	82,696	(11,908)	Dominated

T1: researcher-recommended, T2: farmers' practice, T3: 10% over T2; T4: 20% over T2.
1 USD = BDT 78.2 in June 2013. Note: Explanation of costs and benefits as for Table 3

Table 5
Marginal return to fertilizer treatments for DS rice in five climate/salinity scenarios.

Scenario	Treatment	Nitrogen (kg/ha)	Yield (kg/ha)	Paid-out cost	Marginal cost	Net benefit	Marginal net benefit	Marginal rate of return
				BDT/ha				%
Historical (1984–2013)	T1	220	3.32	5250		54,150		
	T2	300	3.45	6500	1250	56,500	2350	188
	T3	330	3.52	7150	650	55,850	(650)	Dominated
	T4	360	3.57	7800	1300	57,000	500	38
2030	T1	220	3.85	7274		62,027		
	T2	300	3.47	9055	1781	53,945	(8082)	Dominated
	T3	330	3.87	9961	2687	59,340	(2687)	Dominated
	T4	360	3.91	10,866	3592	59,334	(2693)	Dominated
2060	T1	220	4.13	8621		66,079		
	T2	300	3.30	10,530	1909	48,870	(17,209)	Dominated
	T3	330	4.12	11,583	2962	63,117	(2962)	Dominated
	T4	360	4.16	12,636	4015	62,064	(4015)	Dominated

T1: researcher-recommended, T2: farmers' practice, T3: 10% over T2; T4: 20% over T2.
1 USD = BDT 78.2 in June 2013. Note: Explanation of costs and benefits as for Table 3.

could be beneficial now as well as under future conditions. For EWS rice, T2 (farmers' practice) was the optimal treatment under historical conditions, but T3 (a 10% increase in N) was optimal in 2030 and 2060 (Table 4). For dry-season (DS) rice, T2 (farmers' practice) was optimal under historical conditions, but T1 (researchers' recommendation for a *lower* N application) was more beneficial in 2030 and in 2060 (Table 5). In sum, there was some potential for increasing net benefit though increased fertilizer use on WS rice, less so for EWS rice, and none at all for DS rice.

For the non-rice DS grain crops (maize, sunflower, and wheat) there was also little advantage in increased fertilizer application. For maize, T1 (the researcher-recommended reduced dose) was the optimal treatment under historical and 2030 conditions, and T3 (a 10% increase in N over farmers' practice) was optimal in 2060 (Table 6). For sunflower, T3 (a 10% increase) was optimal under historical conditions, but the researchers' lower recommendation (T1) gave better returns in 2030 and 2060 (Table 7). In the case of wheat, T1 (the lower researcher recommendation) was the optimal treatment under historical and future conditions (Table 8).

3.2.2. Profitability with modified sowing dates and salinity mitigation

In this section, the profitability of cropping systems is compared (i) with and without the presence of salinity, assuming farmer's current practices; and (ii) with and without adaptive changes in sowing dates, assuming the ongoing presence of salinity. The impacts of salinity were assessed only for DS and EWS crops as many informants and independent research indicates that WS rice is largely free from the effects of salinity, provided DS shrimp farming is not prolonged and adheres to recommended practices for managing the transition between seasons. The impact of salinity on the rice/watermelon (P1), rice/fallow (P2), and rice/pumpkin (P3) cropping systems was not analysed due to the unavailability of data. Not only is APSIM incapable of simulating the performance of crops like watermelon and pumpkin but no secondary sources were found with plausible data for these crops in southwest coastal Bangladesh. Thus the cropping systems considered in this analysis were systems P4 to P10 (Table 1).

The second set of comparisons was based on the modelling of changes in sowing dates presented in Section 3.1.2. These changes are low-cost adaptations to changes in rainfall and salinity that farmers would be likely to adopt. The results of the modelling for each individual crop were used to select an optimally adapted cropping system (allowing for the fact that a changed starting date for one crop may affect the following crops in the system). Where crops such as watermelon or pumpkin were part of the system, they were included with the same yields and returns as discussed in Kabir et al. (2017a,b), that is, assuming no adaptation. To simplify the presentation, only the results for GI/ha are presented (Table 9).

With the rice/watermelon/rice cropping system (P4), the GI/ha was highest in the absence of salinity across all five climate scenarios. The salinity-induced yield loss of EWS rice reduced the GI/ha of the cropping system by 19–30%, with the size of the impact increasing through time. The unmeasured impact of salinity on DS watermelon would

Table 6
Marginal return to fertilizer treatments for maize in five climate/salinity scenarios.

Scenario	Treatment	Nitrogen (kg/ha)	Yield (kg/ha)	Paid-out cost	Marginal cost	Net benefit	Marginal net benefit	Marginal rate of return
				BDT/ha				%
Historical (1984–2013)	T1	312	4.80	6920		75,884		
	T2	413	4.90	9260	2340	75,539	(345)	Dominated
	T3	454	4.90	10,186	3266	74,713	(1171)	Dominated
	T4	496	4.90	11,112	4192	73,887	(1997)	Dominated
2030	T1	312	5.70	9627		128,482		
	T2	413	5.80	12,874	3247	128,037	(445)	Dominated
	T3	454	5.85	14,161	4534	128,083	(399)	Dominated
	T4	496	5.85	15,449	5822	126,926	(1556)	Dominated
2060	T1	312	6.00	6855		217,898		
	T2	413	6.25	10,102	3247	224,133	6235	192
	T3	454	6.35	11,389	1287	226,610	2477	192
	T4	496	6.35	12,677	1288	225,289	(1321)	Dominated

T1: researcher-recommended, T2: farmers' practice, T3: 10% over T2; T4: 20% over T2.
1 USD = BDT 78.2 in June 2013. Note: Explanation of costs and benefits as for Table 3.

Table 7
Marginal return to fertilizer treatments for sunflower in five climate/salinity scenarios.

Scenario	Treatment	Nitrogen (kg/ha)	Yield (kg/ha)	Paid-out cost	Marginal cost	Net benefit	Marginal net benefit	Marginal rate of return
				BDT/ha				%
Historical (1984–2013)	T1	200	2.70	4420		104,000		
	T2	239	2.70	5280	860	103,220	(780)	Dominated
	T3	263	2.80	5808	1388	106,42	2742	198
	T4	287	2.70	6336	528	102,264	(4478)	Dominated
2030	T1	200	2.55	6150		118,624		
	T2	239	2.45	7347	1197	112,658	(5966)	Dominated
	T3	263	2.60	8082	1932	119,352	728	38
	T4	287	2.60	8816	734	118,683	(669)	Dominated
2060	T1	200	2.40	7181		152,499		
	T2	239	2.25	8578	1397	141,162	(1,1337)	Dominated
	T3	263	2.40	9436	2255	150,486	(2013)	Dominated
	T4	287	2.45	10,294	3113	152,874	375	12

T1: researcher-recommended, T2: farmers' practice, T3: 10% over T2; T4: 20% over T2.
1 USD = BDT 78.2 in June 2013. Note: Explanation of costs and benefits as for Table 3.

Table 8
Marginal return to fertilizer treatments for wheat in five climate/salinity scenarios.

Scenario	Treatment	Nitrogen (kg/ha)	Yield (kg/ha)	Paid-out cost	Marginal cost	Net benefit	Marginal net benefit	Marginal rate of return
				BDT/ha				%
Historical (1984–2013)	T1	221	2.00	4880		41,580		
	T2	240	1.90	5300	420	38,900	(2680)	Dominated
	T3	264	2.00	5830	950	40,720	(860)	Dominated
	T4	288	2.10	6360	1,80	42,540	(960)	65
2030	T1	221	1.90	6791		55,630		
	T2	240	1.80	7375	584	51,844	(3786)	Dominated
	T3	264	1.90	8113	1322	54,426	(1204)	Dominated
	T4	288	1.95	8850	2059	55,225	(405)	Dominated
2060	T1	221	1.75	7928		82,773		
	T2	240	1.65	8610	682	77,004	(5769)	Dominated
	T3	264	1.75	9471	1543	81,397	(1376)	Dominated
	T4	288	1.80	10,332	2404	82,742	(31)	Dominated

T1: researcher-recommended, T2: farmers' practice, T3: 10% over T2; T4: 20% over T2.
1 USD = BDT 78.2 in June 2013. Note: Explanation of costs and benefits as for Table 3.

presumably add to this loss. However, adaptation (i.e., changing the sowing date of WS rice and EWS rice) gave 13–19% higher GI/ha over farmers' practice in the same saline environment across the five climate scenarios. This result indicates that the loss due to salinity with changed sowing dates decreased to 5–11%. That is, the benefits of adaptation almost offset the costs of salinity (Table 9).

With the rice/pumpkin/rice cropping system (P5), once again, in the absence of salinity, even under farmer' practice, this system returned 21–27% higher GI/ha than with salinity across the five climate scenarios. The salinity-induced yield loss of EWS rice caused a 21–27% loss of returns for the cropping system as a whole. The unmeasured impact of salinity on pumpkin would also presumably add to this loss. However, with changed sowing dates of WS rice and EWS rice, the GI/ha was 20–23% higher than with the farmers' practice in a saline environment across all climate scenarios. That is, the benefits of adaptation (increased yield of EWS rice due to escaping the adverse impacts of

Table 9
Gross income per hectare of cropping systems across five climate scenarios with salinity mitigation or adaptation.

Cropping pattern	Adaptation/mitigation option	Gross income per ha (BDT '000)				
		Historical (1984–2013)	2030		2060	
			A2	B1	A2	B1
P4 (rice/water-melon/rice)	Current practice, with salinity	106.5	141.0	125.8	173.8	137.1
	Current practice, with no salinity	126.6	171.4	153.2	213.4	178.0
	Adaptation, with salinity	120.1	162.1	147.6	185.4	162.5
P5 (rice/pump-kin/rice)	Current practice, with salinity	89.3	131.1	114.0	193.4	150.5
	Current practice, with no salinity	109.4	159.1	141.4	229.7	191.4
	Adaptation, with salinity	108.1	156.9	140.3	208.6	185.2
P6 (rice-fish/shrimp)	Current practice, with salinity	159.1	212.8	206.2	303.5	281.0
	Current practice, with no salinity	171.4	240.5	232.2	367.5	346.5
	Adaptation, with salinity	171.4	240.5	232.2	367.5	346.5
P7 (rice/rice)	Current practice, with salinity	56.2	73.4	63.9	120.8	94.6
	Current practice, with no salinity	95.8	114.9	103.0	185.0	158.3
	Adaptation, with salinity	75.9	126.1	109.2	206.0	167.6
P8 (rice/maize)	Current practice, with salinity	106.4	120.2	112.0	169.0	143.0
	Current practice, with no salinity	118.4	140.6	131.5	197.3	175.0
	Adaptation, with salinity	136.1	183.9	167.8	299.8	232.6
P9 (rice/sunflower)	Current practice, with salinity	106.4	120.2	112.0	169.0	143.0
	Current practice, with no salinity	118.4	140.6	131.5	197.3	175.0
	Adaptation, with salinity	136.1	183.9	167.8	299.8	232.6
P10 (rice/wheat)	Current practice, with salinity	49.4	74.6	59.0	127.1	84.7
	Current practice, with no salinity	51.7	82.1	65.0	139.6	93.3
	Adaptation, with salinity	62.1	95.7	73.3	145.9	101.9

Note: Adaption measures were changing sowing dates of WS, EWS, and DS rice, maize, sunflower and wheat, and unspecified options for aquaculture.
1 USD = BDT 78.2 in June 2013.

salinity) almost completely outweighed the cost of salinity, particularly in 2030, reducing the loss to 1–5% across the historical and 2030 climate scenarios, up to 13% in 2060 (Table 9).

The rice-fish/shrimp system (P6) was harder to model. There was no issue here with salinity in the DS and it is unclear exactly what adaptations are expected by aquaculture experts. However, assuming a changed sowing date for WS rice and unspecified adaptations in the shrimp component, there was an increased GI/ha of 8% under historical conditions and 13–23% across the four future climate scenarios (Table 9).

The rice/rice/fallow cropping system (P7) – that is, WS and DS rice – gave 53–70% lower GI/ha than in the absence of salinity under farmers' current management across the five climate scenarios (Table 9). As would be expected, the salinity-induced yield loss of DS rice significantly affected the overall return to this system. However, with changed sowing dates, the system returned 71–77% higher GI/ha compared with farmers' practice across the four future climate scenarios, even in the presence of salinity. It can also be noted that the adapted cropping system gave 10–18% higher GI/ha than with farmers' practice in the *absence* of salinity across the future climate scenarios. This suggests that, in addition to salinity, other environmental factors (e.g., increased temperature and droughts, and inadequate freshwater for irrigation) also affected the productivity and profitability of the rice/rice cropping system under farmers' practice, and that the changed sowing dates reduced these impacts as well. Overall, the costs of salinity and other environmental constraints under farmers' practice would be more than offset by the benefits of adaptation. The changed sowing dates enable the DS crop to exploit a more favourable environment with less moisture stress and salinity.

The rice/maize cropping system (P8) returned 26–38% lower GI/ha with salinity than in the absence of salinity under farmers' practice across the five climate scenarios (Table 9). On the other hand, the rice/maize system in the presence of salinity but with adaptation (i.e., changing the sowing dates of maize and WS rice) gave 13–23% higher GI/ha than farmers' practice across the four future climate scenarios. Changing sowing dates reduced the costs of salinity to a 9–23% loss of GI, instead of the 26–38% under farmers' practice. The main point, however, is that with or without adaptation or mitigation, the GI/ha for this system increases by 2–3 times from historical conditions to 2060 conditions, as reflected in its rise in the rankings as reported in Kabir et al. (2017b).

The rice/sunflower cropping system (P9) was impacted less by salinity, with 11–22% reduction in GI/ha when compared with a salinity-free environment across the five climate scenarios (Table 9). However, with adaptation (i.e., changing the sowing dates of sunflower and WS rice), this system returned significantly higher (53–77%) GI/ha compared with farmers' practice across the four future climate scenarios. Thus adaptation more than offset the impact of salinity, further enhancing the prospects for the adoption of this system in the future. The rice/sunflower system with adaptation in the saline environment returned 33–60% higher GI/ha than farmers' practice in the *absence* of salinity across the future climate scenarios. This result indicates that, besides salinity, other environmental stresses such as temperature, rainfall, droughts, and lack of freshwater for irrigation affected the productivity and profitability of the cropping system under farmers' practice, hence the adaptive measures enabled the DS crop in particular to reduce these environmental stresses and produce higher yields.

Finally, the rice/wheat system (P10) gave only slightly higher (5–10%) GI/ha even in the absence of salinity compared with farmers' practice across the five climate/salinity scenarios (Table 9). This was because the yields of the salt-tolerant variety of wheat were similar with or without salinity under farmers' management. However, the rice/wheat system with adaptation (changed sowing date) returned 15–26% higher GI/ha in the saline environment compared with farmers' practice across the five climate scenarios. The changed sowing date provided a more favourable environment (less soil moisture stress and salinity) and produced higher yields. Again, adaptation more than offset the relatively small cost of salinity and other environmental stresses. The main problem with the rice/wheat option is that it was outperformed by alternative new cropping systems, notably rice/sunflower and rice/maize.

3.2.3. Stochastic dominance analysis with adaptation

With adaptation, but without salinity mitigation, the ranking of the cropping systems based on the cumulative probability distribution

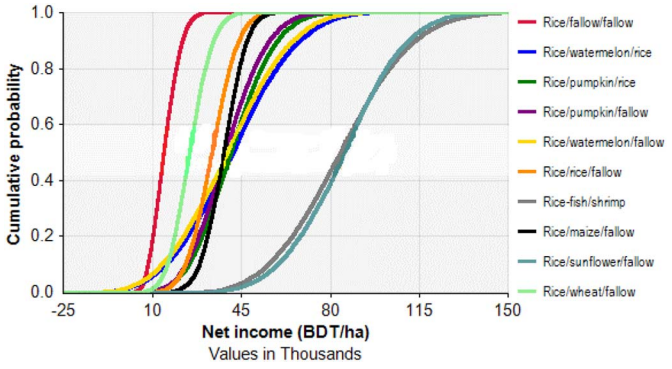

Fig. 12. Cumulative probability distribution (CDF) of net income per ha of cropping systems based on current prices and historical yields with adaptation.

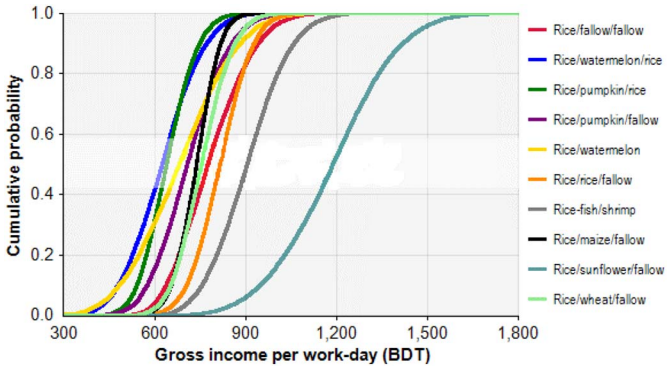

Fig. 13. Cumulative probability distribution (CDF) of gross income per work-day of cropping systems based on current prices and historical yields with adaptation.

functions (CDFs) of net income (NI) per hectare and NI per work-day changed compared with the ranking based on farmers' practice that was discussed in Kabir et al. (2017b). The CDFs generated under historical conditions with adaptation are shown in Figs. 12 and 13, but the CDFs under 2030 and 2060 conditions with adaptation have been omitted; rather, the results of the stochastic dominance analysis are presented in table form below.

3.2.3.1. Historical conditions. Under historical conditions, the CDF of NI/ha for the rice/sunflower system (P9) moved far to the right, beyond the rice-fish/shrimp system; the CDFs for most rice/non-rice systems were in the middle, and the CDF for the rice/fallow system was pushed further to the left. Thus the rice/sunflower system showed first-degree stochastic dominance (FSD) over all other systems and the rice-fish/shrimp system (P6) showed FSD over other systems apart from rice/sunflower. The rice/watermelon/rice system (P4) also improved its ranking with adaptation and showed second-degree stochastic dominance (SSD) or FSD over the other rice/non-rice systems. The ranking of rice/rice (P7) and rice/wheat (P10) systems remained unchanged while the ranking of the rice/maize system (P8) fell to ninth from seventh. It can be noted that the probability of generating a positive NI per hectare increased for the cropping systems under adaptation to at least 98% instead of 85% under farmers' management (Table 10 and Fig. 12).

Still under historical conditions but ranking by the distribution of GI per work-day of family labour, the rice/sunflower system with adaptation again showed FSD over all other systems, followed by the rice-fish/shrimp system. The rice/rice system with adaptation showed SSD or FSD over rice/non-rice cropping systems (apart from rice/sunflower). The ranking of rice/watermelon and rice/pumpkin systems fell to seventh and eighth, respectively, instead of fourth and fifth under farmers' practice, while the ranking of the rice/maize system with adaptation moved up to sixth from tenth (Table 11 and Fig. 13).

Table 10
Stochastic dominance ranking of cropping systems with adaptation under historical and future climate/salinity scenarios based on NI/ha (= denotes equal ranking).

Cropping pattern	Historical (1984–2013)	2030		2060	
		A2	B1	A2	B1
P1: Rice/watermelon/fallow	4	= 8	8	9	9
P2: Rice/fallow/fallow	10	10	10	10	10
P3: Rice/pumpkin/fallow	3	4	= 4	6	6
P4: Rice/watermelon/rice	6	7	7	8	7
P5: Rice/pumpkin/rice	5	3	3	4	4
P6: Rice-fish/shrimp	2	1	1	1	1
P7: Rice/rice/fallow	8	5	= 4	5	5
P8: Rice/maize/fallow	7	6	= 4	3	3
P9: Rice/sunflower/fallow	1	2	2	2	2
P10: Rice/wheat/fallow	9	= 8	9	7	8

Table 11
Stochastic dominance ranking of cropping systems with adaptation under historical and future climate/salinity scenarios based on GI/work-day of family labour.

Cropping patterns	Historical (1984–2013)	2030		2060	
		A2	B1	A2	B1
P1: Rice/watermelon/fallow	8	= 9	9	9	10
P2: Rice/fallow/fallow	4	= 4	4	6	5
P3: Rice/pumpkin/fallow	7	7	6	7	7
P4: Rice/watermelon/rice	10	= 9	10	10	9
P5: Rice/pumpkin/rice	9	8	8	8	8
P6: Rice-fish/shrimp	2	2	2	3	2
P7: Rice/rice/fallow	3	3	3	2	4
P8: Rice/maize/fallow	6	6	5	= 4	3
P9: Rice/sunflower/fallow	1	1	1	1	1
P10: Rice/wheat/fallow	5	= 4	7	= 4	6

3.2.3.2. 2030 conditions[1]. Under 2030 conditions of climate and salinity, the rice-fish/shrimp system (P6) with adaptation returned to first ranking in terms of NI/ha, showing FSD over all other systems across both pessimistic and optimistic climate scenarios (Table 10). The rice/sunflower system (P9) with adaptation moved back to second rank, showing FSD over all other rice/non-rice cropping systems. Of the other rice/non-rice cropping systems, the rice/pumpkin/rice system (P5) improved its ranking with adaptation and showed at least SSD over the other rice/non-rice systems apart from rice/sunflower. Of the existing rice/non-rice cropping systems, the rice/watermelon (P1) and rice/pumpkin (P3) systems reduced their ranking to eighth and ninth, respectively, compared with fourth and third under farmers' practice. This may be because no adaptation options were available for watermelon and pumpkin. With adaptation, the ranking of the rice/maize (P8) and rice/wheat (P10) systems remained largely unchanged while the ranking of the rice/rice system (P7) improved to fourth or fifth, depending on the climate scenario. The probability of generating a positive NI/ha increased with adaptation to at least 98% for all cropping systems except rice/watermelon and rice/wheat under the optimistic scenario.

In terms of GI per work-day, after adaptation the rice/sunflower system (P9) showed FSD over all other systems while the rice-fish/shrimp system (P6) showed FSD over the other systems apart from P9 (Table 11). Of the other cropping systems, the rice/rice system improved its ranking with adaptation, as did the rice/pumpkin system (P3).

3.2.3.3. 2060 conditions. Using the distributions of NI/ha, the rice-fish/shrimp system (P6) with adaptation again showed FSD over all other

[1] Risk analyses for future scenarios are not shown in the paper for reasons of space but are available from the corresponding author on request.

Table 12
Adapted cropping systems through changing sowing dates.

System	Wet season		Dry season		Early wet season	
	Crop	Date	Crop	Date	Crop	Date
P1	Rice	1–7 Sep	Watermelon	1–7 Feb	Fallow	
P2	Rice	1–7 Sep	Fallow		Fallow	
P3	Rice	1–7 Sep	Pumpkin	1–7 Feb	Fallow	
P4	Rice	15–18 Sep	Watermelon	8–15 Feb	Rice	1–7 Jun
P5	Rice	15–18 Sep	Pumpkin	8–15 Feb	Rice	1–7 Jun
P6	Rice	15–18 Sep	Shrimp	10–20 Feb	Shrimp	
P7	Rice	15–18 Sep	Rice	1–30 Apr	Fallow	
P8	Rice	1–7 Sep	Maize	7–15 Dec	Fallow	
P9	Rice	15–18 Sep	Sunflower	1–30 Mar	Fallow	
P10	Rice	1–7 Sep	Wheat	7–15 Dec	Fallow	

systems in 2060, followed by the rice/sunflower system (P9) (Table 10). The rice/maize system (P8) further improved its ranking at the expense of the rice/rice and rice/pumpkin/rice systems. Despite adaptation, the ranking of the rice/wheat system did not improve. The probability of generating a positive NI/ha increased with adaptation from at least 85–95% to 100% for all cropping systems except rice/watermelon.

Comparing the CDFs of GI/work-day, the rice/sunflower system (P9) with adaptation showed FSD over all other systems (Table 11). The rice-fish/shrimp system (P6) was ranked second under the optimistic climate scenario while the rice/rice system was ranked second under the pessimistic climate scenario, with rice/maize (P8) moving into third rank in this scenario.

4. General discussion

Allowing for farmer adaptation is crucial to assessing the likely impacts of climate change and salinization in coastal Bangladesh. The IPCC in its fourth assessment report collated a wide range of published simulated data sets on projected changes to yields of major cereals (rice, wheat, and maize). They found that, worldwide, adaptations such as changing varieties and sowing times would have a 10–15% yield benefit for cereals, despite 1–2 °C local temperature increase. It was also found that, in low latitudes (tropical and subtropical regions), adaptation could lead to increased maize yield, while rice and wheat yields would likely increase by 5–7%, despite 1–2 °C warming (Easterling et al., 2007).

Several adaptation options were explored in this paper to offset negative impacts of climate change and salinization – crop varieties, fertilizer use, and sowing date. Perhaps the most important of these was the incorporation of new DS crops – wheat, maize, and sunflower. Of these, the rice/sunflower cropping system was consistently the best performer, using various criteria and across current and future scenarios. The rice/maize system also appeared a promising alternative, especially in the 2060 scenarios, but even a saline-tolerant wheat variety did not rank highly. Farmers could potentially benefit even now from adding sunflower or maize to their cropping system.

Adaptation though changed fertilizer use (higher or lower, depending on the crop) could give higher returns for some cropping systems. A 10–20% increase in nitrogen application over farmers' current practice would give higher returns for rice/fallow, rice/watermelon/rice, rice/pumpkin/rice, and rice/maize cropping systems across future conditions. Improved fertilizer management would also increase future returns to the rice/rice, rice/sunflower and rice/wheat cropping systems.

However, larger improvements in net benefits were obtainable with low-cost changes in sowing dates to avoid the worst stresses imposed by climate change and salinity. Changing sowing dates to earlier in the DS (as shown in Table 12) could reduce the salinity-induced yield loss of maize, wheat, and sunflower, make better use of residual moisture from the WS, and also establish crops in periods of higher physiological yield potential (i.e., escaping high temperature problems). Mondal et al. (2015a) have earlier demonstrated advantages to early sowing of DS rice in this region. Nevertheless, stagnant water is a potential barrier to adopting early sowing of some crops. Engineering interventions for improved drainage and/or better community co-ordination of polder water management may offer the possibility to achieve successful early sowing (Mondal et al., 2015b).

Conversely, later sowing options were projected to give improved performance (higher yield with less seasonal variability) for WS rice, DS rice, EWS rice, and sunflower. Hence the late sowing options could be more efficacious adaptations to the combined effects of climate change and salinization. The projected increased precipitation for late-planted crops along with increased atmospheric CO_2 appeared to outweigh the adverse impacts of rising temperature and salinity. The increased precipitation is projected to have a significant role in promoting stable yields as it is expected to create more congenial cropping conditions by flushing salt from the topsoil and diluting irrigation water, thereby increasing nitrogen- and water-use efficiency.

With such adaptations, and allowing for risk, the rice/shrimp system maintains the top ranking in terms of income per ha in 2030 and 2060 and the rice/sunflower system maintains the second ranking (though it outperforms rice/shrimp in terms of NI/work-day). The rice/pumpkin/rice system ranked third for 2030 and fourth in 2060 while the rice/maize system moved up to third in 2060. Hence the results imply that rice-based cropping systems in south-west coastal Bangladesh are likely to be modified in coming decades, with the choice depending on the particular local conditions and farmers' goals and circumstances.

The analysis of cropping system performance in the absence of salinity confirmed the findings in Kabir et al. (2017b) that the economic impact of salinization is and will be severe, hence the benefits of salinity mitigation, if feasible, are likely to be substantial. The improved returns due to adaptation, however, enabled farmers to offset or avoid much of the adverse economic impact of salinity.

5. Conclusion

Climate change and salinization are expected to have a major impact on agriculture in the south-west coastal zone of Bangladesh in coming decades. However, not all the impacts are negative and it is likely that rice-based cropping systems will continue to be viable – that is, systems building on a wet-season rice crop. This is especially so if we allow for farmer adaptation to current and emerging constraints. The analysis indicates that the rice/shrimp system will continue to be a dominant option where local conditions are suitable and sustainable practices are implemented. With respect to dry-season cropping, the incorporation of alternative crops such as sunflower and maize appears to be a promising adaptation. The performance of most crops (existing and novel) is projected to improve with adaptations in crop management (changed sowing dates and, in some cases, changed fertilizer use) across the future scenarios. The loss of production due to climate change and increased salinity can be largely offset with appropriate adaptations. Thus, while the rice/shrimp system is likely to persist in some locations, in other cases there is likely to be a switch from the currently dominant rice/watermelon system to adapted forms of rice/sunflower, rice/maize, rice/rice, and rice/pumpkin/rice cropping systems. It is likely, too, that further research will result in better adapted varieties and improved cropping technologies to provide additional adaptation options for farmers.

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